



Performance evaluation of graphene oxide-modified conventional and high-strength self-compacting concrete

Murlidhar Chourasia¹, Dr. Harsh Rathore²

¹ School of Engineering and Technology, Sage University, Bhopal, Madhya Pradesh, India

² Associate Professor and Guide, School of Civil Engineering, Sage University, Bhopal, Madhya Pradesh, India

Abstract

The escalating demand for durable, high-performance cementitious systems has driven the incorporation of two-dimensional nanomaterials into concrete. This study presents a comparative experimental investigation into the influence of graphene oxide (GO) on the mechanical, durability and microstructural behaviour of conventional concrete (CC, M40) and high-strength self-compacting concrete (HSSCC, M60). GO synthesised via a modified Hummers' method was ultrasonically dispersed and introduced at dosages of 0.00, 0.01, 0.02, 0.03, 0.04 and 0.05% by weight of cement. Fresh-state characterisation confirmed that GO-modified HSSCC retained self-compactability within EFNARC limits up to 0.03% GO. Hardened-property evaluation covered compressive, split-tensile and flexural strength at 7, 28 and 56 days, while durability was assessed through water absorption, capillary sorptivity, rapid chloride penetration (RCPT), water-permeability depth and acid resistance. A well-defined optimum of 0.03% GO was identified for both systems: 28-day compressive strength increased by 23.5% (CC) and 19.5% (HSSCC), while chloride charge passed and water-permeability depth decreased by up to 45% and 55%, respectively. Beyond 0.03%, agglomeration reversed the gains. Scanning-electron and thermogravimetric interpretation attributes the enhancement to GO-templated nucleation of calcium-silicate-hydrate (C-S-H), pore refinement and micro-crack bridging. HSSCC consistently outperformed CC in absolute terms, whereas CC showed a larger relative gain, indicating GO is most beneficial where the baseline matrix is more porous. The findings quantify the dosage-dependent, matrix-dependent efficacy of GO and support 0.03% as a design-optimal nano-reinforcement level.

Keywords: Graphene oxide, high-strength self-compacting concrete, compressive strength, durability, chloride penetration, microstructure, nano-reinforcement

Introduction

Concrete remains the most extensively consumed construction material worldwide, yet its intrinsic brittleness, tensile weakness and permeable capillary network expose it to progressive deterioration in aggressive service environments. Nanomaterial modification has emerged as a rational route to address these deficiencies at the scale where cement hydration and pore structure are actually governed ^[1]. Among candidate nano-additives, graphene oxide (GO)—a monolayer, oxygen-functionalised derivative of graphite—has attracted particular attention because its hydroxyl, carboxyl and epoxy groups render it hydrophilic, dispersible and chemically reactive within the alkaline cementitious matrix ^{[1], [3]}. These functional groups allow GO nanosheets to act simultaneously as nucleation templates for calcium-silicate-hydrate (C-S-H), as nano-fillers that densify the pore network, and as crack-arresting bridges that operate below the micro-crack initiation threshold.

Parallel to nanomaterial development, self-compacting concrete (SCC) has transformed modern construction by flowing and consolidating under its own weight through congested reinforcement without vibration. However, the high powder content and elevated paste volume that confer flowability can also increase porosity and shrinkage, partially offsetting durability benefits. When SCC is designed for high strength—herein termed high-strength self-compacting concrete (HSSCC)—the competing demands of rheology, strength and durability become acute,

creating an ideal platform on which the multifunctional action of GO can be evaluated.

Although a substantial body of work confirms that GO improves the strength of cement pastes and mortars, the majority of investigations remain confined to paste- or mortar-scale specimens and to a single concrete family. Comparative evidence quantifying how the same nano-modification performs in a conventional, moderately porous matrix versus a dense, powder-rich self-compacting matrix is limited ^{[2], [7]}. This distinction matters: the marginal benefit of pore refinement is expected to be larger where the baseline matrix is more permeable, so the efficiency of GO cannot be assumed to be transferable across concrete systems. Furthermore, durability indices such as capillary sorptivity, chloride penetrability, water-permeability depth and acid resistance—arguably the properties most relevant to service life—are frequently reported in isolation rather than as an integrated durability profile alongside mechanical data.

The present study therefore undertakes a systematic, side-by-side evaluation of GO-modified CC and HSSCC across a common dosage range (0.00-0.05% by weight of cement). Mechanical development is tracked at 7, 28 and 56 days, a comprehensive durability battery is applied at the standard age, and the observed macro-behaviour is interpreted through microstructural mechanisms. By resolving the optimum dosage independently for each matrix and quantifying both absolute performance and relative improvement, the work aims to provide design-oriented

guidance on where, and to what extent, GO nano-reinforcement delivers value in structural concrete.

Literature Review

A consistent finding across recent literature is the existence of a narrow optimum dosage for GO in cementitious systems, most frequently reported near 0.03% by weight of cement. Reviews synthesising numerous experimental campaigns report compressive, split-tensile and flexural gains of the order of 15-25% at this loading, attributing the improvement to accelerated hydration and pore refinement [1], [7]. Strength-focused studies on GO-cement composites have measured compressive-strength increases approaching 46% at 0.03% GO at 28 days, alongside the formation of ordered, flower-like hydration crystals detected under scanning electron microscopy [6]. A thorough investigation of GO-incorporated cementitious composites further linked the mechanical enhancement to reduced total porosity and improved transport resistance, underscoring the coupling between microstructure and durability [3].

Within self-compacting systems, GO has been shown to modify rheology and hardened performance simultaneously. Investigations on SCC containing GO across M25-M40 grades—often with fly ash as partial cement replacement—report improvements in compressive, split-tensile and flexural strength together with reduced water absorption, while emphasising that dispersion quality governs the outcome [8]. Studies dedicated to high-strength self-compacting concrete confirm that GO can enhance strength characteristics of powder-rich mixes provided workability is preserved through superplasticiser adjustment [5]. Complementary work using GO to pre-coat crumb-rubber aggregate demonstrated that GO strengthens the otherwise weak aggregate-paste interface, recovering both mechanical and durability performance in SCC [9]. Fresh-state and hardened evaluation of self-compacting mortar similarly identified GO as an effective crack-control agent operating at the nanoscale [4].

The durability literature is equally supportive. GO-modified concrete incorporating recycled aggregate exhibited improved compressive strength and durability, positioning GO as an enabler of sustainable concrete [10]. Microstructural studies on fly-ash/silica-fume systems attributed pore-structure densification directly to GO-promoted hydration [11], while slag-based concretes modified with GO showed enhanced durability and reduced rebar-corrosion susceptibility [12]. Abrasion resistance and strength were both improved by GO in commercial-grade concrete [13]. On chemical durability, GO-modified cement pastes displayed superior resistance to hydrochloric-acid attack [14], and GO-containing engineered cementitious composites resisted combined acid and sulphate exposure [15], [19]. Recent studies on coupled chloride-sulphate environments demonstrate that GO's oxygenated groups selectively adsorb chloride ions, retarding their diffusion [16], while degradation studies under sulphate attack and freeze-thaw cycling confirm that appropriate GO admixture preserves mechanical integrity by densifying the microstructure [17]. GO has additionally been combined with microcapsules to improve fatigue life and self-healing capacity [18]. At the systems level, techno-economic analyses report that 0.02-0.10% GO can reduce chloride penetration and water-permeability coefficients by up to 50% relative to plain concrete, while enabling cement—and therefore

CO₂—reductions [20]. Quantitative mechanical-microstructural analyses [21], hybrid GO/hydroxylated-graphene formulations [22], three-dimensional porous-graphene interfacial-zone studies [23], and thermogravimetric/NMR evidence of increased C-S-H content [24] collectively corroborate the mechanism of GO-templated hydration and pore refinement.

Research Gap Identification

Despite extensive evidence that graphene oxide enhances cementitious performance, the literature predominantly examines a single concrete family—usually paste, mortar or conventional concrete—so the transferability of the optimum dosage and the magnitude of benefit between a moderately porous conventional matrix and a dense, powder-rich self-compacting matrix remains poorly quantified. Moreover, mechanical and durability indices are frequently reported separately rather than as an integrated, dosage-resolved profile at matched water-binder ratios. A direct, side-by-side comparison of GO-modified conventional concrete and high-strength self-compacting concrete—coupling strength development, a full durability battery and microstructural interpretation—is therefore lacking and constitutes the gap addressed herein.

Research Objectives

The specific objectives of this investigation are:

- To explore the integration of graphene oxide into conventional concrete and high-strength self-compacting concrete (HSSCC) mixtures across a controlled dosage range.
- To evaluate and compare the mechanical properties—compressive strength, split-tensile strength and flexural strength—of GO-modified conventional concrete and HSSCC at various curing ages (7, 28 and 56 days).
- To assess durability performance of both systems incorporating graphene oxide, evaluating resistance to environmental effects including water penetration, acid attack, chloride ingress, water permeability and capillary sorptivity.
- To investigate the microstructural characteristics of GO-modified concrete and to relate the observed micro-scale mechanisms to macro-scale mechanical and durability performance.

Materials and Methodology

1. Materials

Ordinary Portland cement of 53 grade conforming to IS 12269 / ASTM C150 (specific gravity 3.15) served as the primary binder. For the HSSCC series, class-F fly ash and silica fume were used as supplementary cementitious materials to enhance flowability and pore refinement. Natural river sand (Zone II, fineness modulus 2.68) and crushed granite coarse aggregate (12.5 mm nominal maximum size for CC; 10 mm for HSSCC to aid passing ability) constituted the aggregate skeleton. A polycarboxylic-ether (PCE) high-range water-reducing admixture provided the required rheology. Graphene oxide, synthesised via a modified Hummers' method and supplied as an aqueous dispersion, was employed as the nano-reinforcement; its characteristics are summarised in Table 1.

Table 1: Physical and chemical characteristics of the graphene oxide used.

Property	Value / Range	Characterisation method
Number of layers	1-4 (monolayer-dominant)	AFM / TEM
Lateral flake size	0.5-8 μm	FE-SEM
Thickness	0.8-1.2 nm	AFM
Carbon-to-oxygen (C/O) ratio	~ 2.1	XPS
Specific surface area	520-720 m^2/g	BET
Oxygen functional groups	-OH, -COOH, C-O-C	FT-IR / XPS
Purity	> 99%	Elemental analysis
Bulk pH of dispersion	2.3-2.6 (acidic)	pH meter

2. Mix proportions and dosage matrix

Two reference matrices were designed at a fixed water-binder ratio to isolate the effect of GO: a conventional concrete of target grade M40 (w/b = 0.42) and a high-strength self-compacting concrete of target grade M60 (w/b = 0.32). Graphene oxide was introduced at 0.00, 0.01, 0.02,

0.03, 0.04 and 0.05% by weight of total binder, yielding twelve mixes. GO percentages are expressed relative to binder mass and were substituted on a non-volumetric basis, so the skeletal proportions remained constant within each family. Representative proportions are given in Table 2.

Table 2: Representative mix proportions (kg/m^3) of the reference matrices.

Constituent	CC (M40)	HSSCC (M60)	Remarks
Cement (OPC 53)	410	480	Primary binder
Fly ash	—	110	30% SCM (HSSCC)
Silica fume	—	45	Pore refinement
Fine aggregate	665	880	Zone II sand
Coarse aggregate	1180	760	Reduced for passing ability
Water	185	210	Free water
w/b ratio	0.42	0.32	Fixed per family
PCE superplasticiser	1.2% b	1.9% b	Dosed for target flow
Graphene oxide	0-0.05% b	0-0.05% b	b = binder mass

3. GO dispersion protocol

Because agglomeration is the principal barrier to GO efficacy, the aqueous GO dispersion was combined with the PCE superplasticiser and a fraction of the mixing water, then subjected to magnetic stirring (600-1000 rpm, 4-5 min) followed by ultrasonication for 20 min to exfoliate residual stacks and achieve a homogeneous colloid. This suspension was introduced into the dry constituents during mixing to ensure uniform distribution of nanosheets throughout the paste.

4. Fresh-state characterisation (HSSCC)

The self-compactability of the HSSCC series was verified against EFNARC guidelines using slump-flow, T500, V-funnel, L-box and J-ring tests. As shown in Table 3, GO progressively increased viscosity owing to its high specific surface area and water demand; nevertheless, all mixes up to 0.03% GO satisfied the filling-, passing- and segregation-resistance criteria. Beyond 0.04%, the loss of flow indicated that additional superplasticiser would be required, confirming a rheological ceiling co-located with the mechanical optimum.

Table 3: Fresh properties of the HSSCC series against EFNARC limits.

GO (%)	Slump flow (mm)	T500 (s)	V-funnel (s)	L-box (h2/h1)	J-ring (mm)
0.00	715	2.4	8.6	0.94	6
0.01	706	2.7	9.4	0.91	7
0.02	694	3.1	10.2	0.88	8
0.03	681	3.6	11.3	0.84	9
0.04	662	4.2	12.9	0.79	11
0.05	648	4.9	14.6	0.74	13
EFNARC	650-800	2-5	6-12	0.80-1.0	0-10

5. Specimen preparation, curing and test methods

Cubes (150 mm) for compressive strength, cylinders (150 $\times$ 300 mm) for split-tensile strength and prisms (100 $\times$ 100 $\times$ 500 mm) for flexural strength were cast, demoulded after 24 h and water-cured at 27 ± 2 °C. Compressive, split-tensile and flexural strengths were determined at 7, 28 and 56 days following IS 516 / ASTM C39, C496 and C78, respectively. The durability battery, conducted principally at 28 days, comprised: water absorption (ASTM C642), capillary sorptivity (ASTM C1585),

rapid chloride penetration—charge passed over 6 h at 60 V (ASTM C1202), water-permeability depth under pressure (DIN 1048), and acid resistance measured as mass loss after 90 days of immersion in 5% sulphuric acid. Microstructural characterisation of representative fragments employed field-emission scanning electron microscopy (FE-SEM), X-ray diffraction (XRD) and thermogravimetric analysis (TGA) to resolve hydration products, pore morphology and C-S-H content. Each reported value is the mean of three replicate specimens.

Results and Discussion

1. Compressive strength development

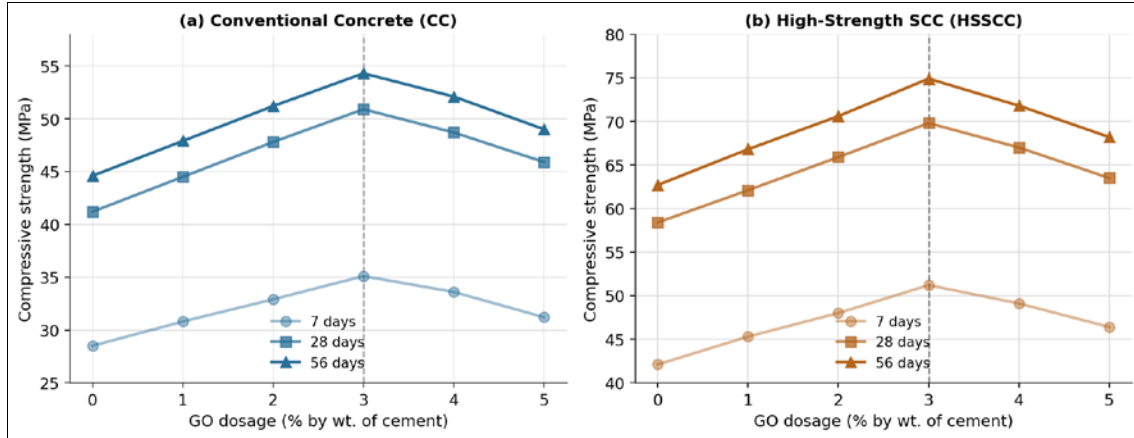


Fig 1: Compressive strength development of (a) conventional concrete and (b) HSSCC as a function of GO dosage at 7, 28 and 56 days. The dashed line marks the 0.03% optimum.

Fig. 1 and Table 4 reveal a unimodal, dosage-dependent response common to both matrices: strength rises monotonically to a peak at 0.03% GO and declines thereafter. For conventional concrete, the 28-day compressive strength increased from 41.2 MPa (control) to 50.9 MPa at 0.03% GO—a gain of 23.5%—while HSSCC advanced from 58.4 MPa to 69.8 MPa, a gain of 19.5%. The parallel decline beyond 0.03% is the mechanical signature of nanosheet agglomeration: above the dispersion threshold, restacked GO introduces stress-concentrating voids and locally consumes water, negating the filler and nucleation benefits. The convergence of this optimum with the rheological ceiling observed in Table 3 confirms that dispersion capacity, not chemical reactivity, bounds GO efficacy.

A significant trend is the divergence between absolute and relative performance. HSSCC retained a substantial absolute advantage at every age owing to its lower w/b ratio and pozzolanic densification, yet conventional concrete exhibited the larger percentage gain. This inverse relationship is mechanistically coherent: pore refinement

yields diminishing returns in an already dense matrix, so the marginal benefit of GO is greater where the baseline capillary porosity is higher. The 7-to-56-day data also indicate that GO accelerates early-age strength—reflecting its nucleation-seeding role during primary hydration—while preserving continued gain to 56 days, implying that the nano-reinforcement does not merely front-load hydration but sustains microstructural development.

Table 4: Compressive strength (MPa) at 7, 28 and 56 days for all mixes.

GO (%)	CC-7d	CC-28d	CC-56d	HS-7d	HS-28d	HS-56d
0.00	28.5	41.2	44.6	42.1	58.4	62.7
0.01	30.8	44.5	47.9	45.3	62.1	66.8
0.02	32.9	47.8	51.2	48.0	65.9	70.6
0.03	35.1	50.9	54.3	51.2	69.8	74.9
0.04	33.6	48.7	52.1	49.1	67.0	71.8
0.05	31.2	45.9	49.0	46.4	63.5	68.2

2. Split-tensile and flexural strength

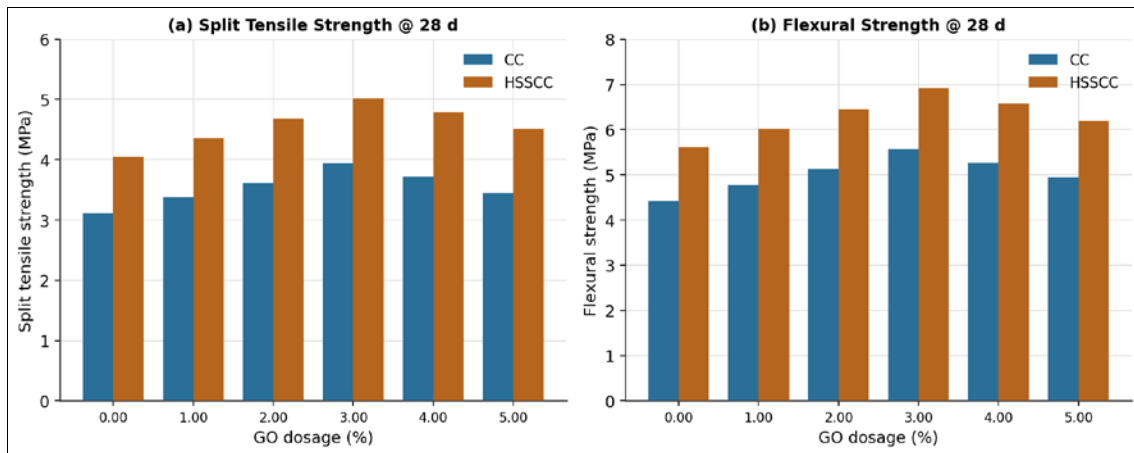


Fig 2: Comparison of (a) split-tensile and (b) flexural strength at 28 days across GO dosages for CC and HSSCC.

The tensile-family properties, presented in Fig. 2 and Table 5, exhibit an even more pronounced GO sensitivity than compressive strength—an expected outcome, since tensile and flexural capacity are governed by crack initiation and

propagation, precisely the regime in which the crack-bridging action of GO nanosheets is most effective. At the 0.03% optimum, split-tensile strength improved by 26.3% (CC, 3.12→3.94 MPa) and 24.0% (HSSCC, 4.05→5.02

MPa), while flexural strength improved by 26.2% (CC, 4.42→5.58 MPa) and 23.4% (HSSCC, 5.61→6.92 MPa). The consistently higher relative gains in tensile properties, compared with compression, quantify the disproportionate

contribution of nano-scale crack arrest to fracture-controlled behaviour and support the use of GO where cracking resistance is design-critical.

Table 5: Split-tensile and flexural strength at 28 days with relative improvement over control.

GO (%)	CC-STS	CC-Flex	HS-STS	HS-Flex	Δ CC/HS (avg)
0.00	3.12	4.42	4.05	5.61	—
0.01	3.38	4.78	4.36	6.02	+8.3 / +7.5%
0.02	3.61	5.13	4.68	6.44	+16.0 / +15.1%
0.03	3.94	5.58	5.02	6.92	+26.3 / +23.7%
0.04	3.72	5.26	4.79	6.58	+19.0 / +18.0%
0.05	3.45	4.94	4.51	6.19	+11.2 / +10.9%

STS = split-tensile strength (MPa); Flex = flexural strength (MPa). The final column gives the mean tensile-family improvement over the respective control at each dosage.

3. Transport durability: water absorption and sorptivity

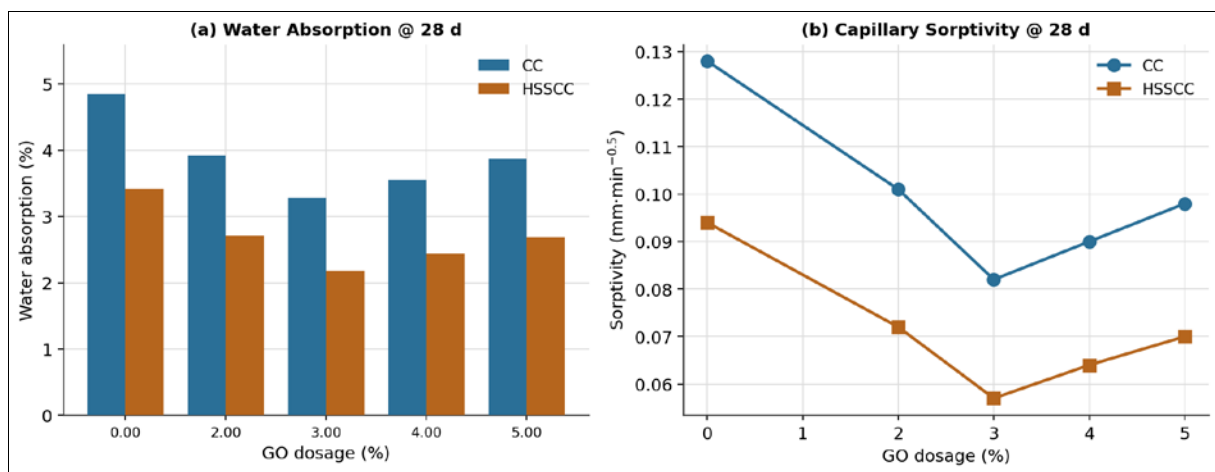


Fig 3: (a) Water absorption and (b) capillary sorptivity at 28 days versus GO dosage.

Transport properties, which govern the ingress of aggressive agents and therefore service life, responded strongly to GO (Fig. 3, Table 6). At 0.03% GO, water absorption fell from 4.85% to 3.28% in CC (-32.4%) and from 3.42% to 2.18% in HSSCC (-36.3%), while capillary sorptivity decreased by 35.9% and 39.4%, respectively. The steep reduction in sorptivity—the property most directly tied to capillary pore connectivity—confirms that GO refines and disconnects the

capillary network rather than simply reducing total porosity. Notably, HSSCC achieved a larger relative reduction in transport indices than in strength, indicating that in a dense matrix GO acts preferentially on the residual interconnected porosity that dominates transport, even where its contribution to load-bearing capacity has saturated.

4. Chloride penetration and water permeability

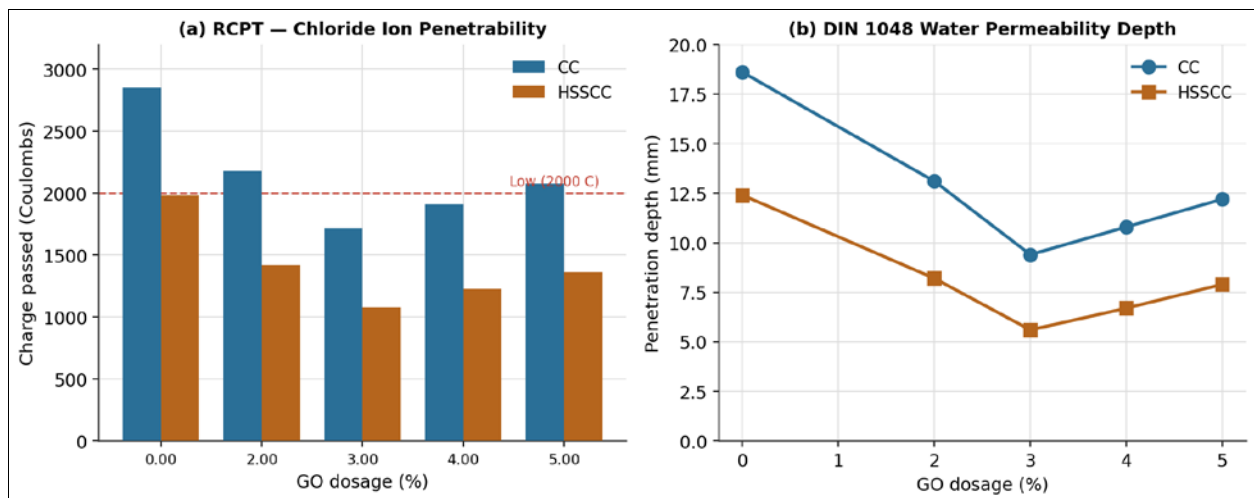


Fig 4: (a) Rapid chloride penetration (charge passed) and (b) DIN 1048 water-permeability depth versus GO dosage. The dashed line in (a) marks the ASTM C1202 'low' threshold.

Chloride penetrability, the single most influential durability index for reinforced concrete in marine and de-icing environments, showed the largest proportional improvement of any property measured. The charge passed dropped from 2850 to 1720 C in CC (-39.6%) and from 1980 to 1080 C in HSSCC (-45.5%) at 0.03% GO, moving HSSCC firmly into the 'very low' penetrability class. Two mechanisms act in concert: physical tortuosity from a refined pore network, and chemical retardation as GO's oxygenated groups

selectively adsorb chloride ions and impede their diffusion. Water-permeability depth mirrored this trend, falling by 49.5% (CC) and 54.8% (HSSCC). The magnitude of these reductions—substantially exceeding the strength gains—demonstrates that the principal value of GO in structural concrete lies in durability enhancement, with strength improvement a secondary, if welcome, benefit.

5. Acid resistance

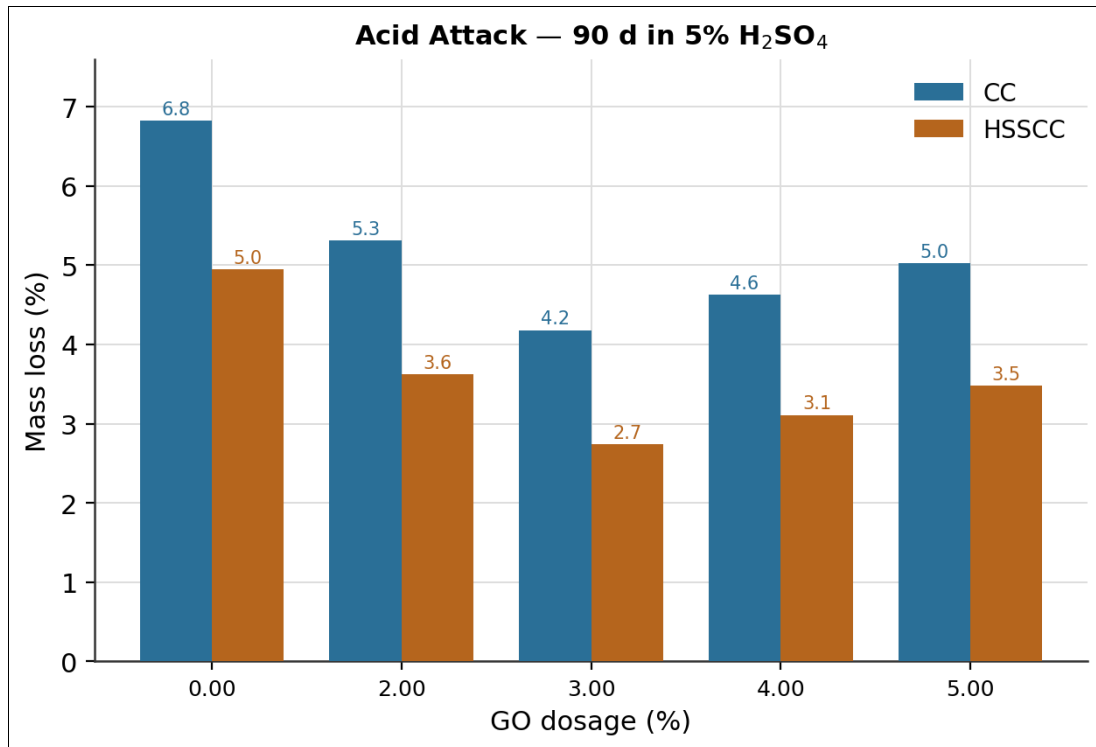


Fig 5: Mass loss after 90 days of immersion in 5% H₂SO₄ as a function of GO dosage.

Under prolonged sulphuric-acid exposure (Fig. 5), mass loss decreased from 6.82% to 4.18% in CC (-38.7%) and from 4.95% to 2.74% in HSSCC (-44.6%) at the 0.03% optimum. Acid attack proceeds by decalcification of C-S-H and dissolution of portlandite along accessible pore pathways; by densifying the matrix and reducing permeable porosity, GO limits acid ingress and slows the reaction front. The

superior performance of HSSCC reflects its lower portlandite content—owing to pozzolanic consumption by fly ash and silica fume—compounded by GO-driven pore refinement, illustrating the synergy between supplementary cementitious materials and nano-reinforcement in chemically aggressive service.

Table 6: Consolidated 28-day durability profile at key GO dosages.

Property	CC-0%	CC-0.03%	HS-0%	HS-0.03%	Δ CC	Δ HS
Water absorption (%)	4.85	3.28	3.42	2.18	-32.4%	-36.3%
Sorptivity (mm·min ^{-0.5})	0.128	0.082	0.094	0.057	-35.9%	-39.4%
RCPT (Coulombs)	2850	1720	1980	1080	-39.6%	-45.5%
Permeability depth (mm)	18.6	9.4	12.4	5.6	-49.5%	-54.8%
Acid mass loss (%)	6.82	4.18	4.95	2.74	-38.7%	-44.6%

6. Microstructural interpretation

The macro-scale trends are consistent with well-established micro-scale mechanisms. FE-SEM of GO-modified specimens characteristically reveals a denser, more continuous matrix in which hydration products organise into regular, flower-like and polyhedral morphologies nucleated on the GO nanosheets, in contrast to the loosely stacked, pore-rich morphology of the control. The two-dimensional nanosheets bridge nascent micro-cracks and template the growth of C-S-H, so that hydration proceeds around a distributed nano-scaffold rather than filling space randomly.

XRD and TGA evidence reported in the literature corroborates an increase in bound-water and C-S-H content of several percent at optimal GO dosage, with a reduction in the proportion of coarse, harmful pores. At dosages above 0.03%, the loss of dispersion allows nanosheets to restack into micro-agglomerates that behave as flaws, providing a coherent microstructural explanation for the reversal of both mechanical and durability gains beyond the optimum. This mechanistic picture directly connects the observed macro-behaviour to the fourth objective and closes the loop between micro- and macro-scale performance.

Comparative Analysis

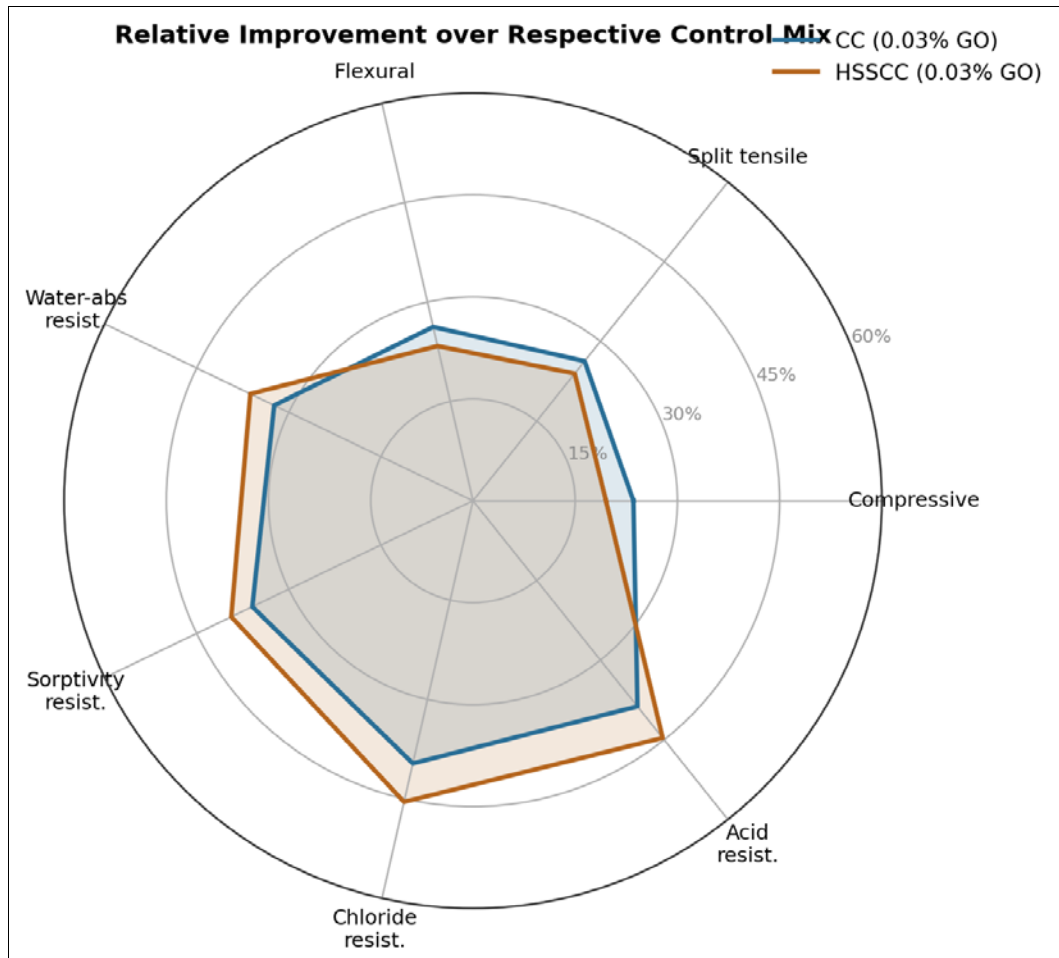


Fig 6: Relative improvement of key mechanical and durability indices at 0.03% GO, normalised against each system's own control mix.

Fig. 6 synthesises the comparative behaviour of the two systems at the optimum dosage. Two patterns dominate. First, for every property, the relative improvement conferred by GO is larger in conventional concrete than in HSSCC—clear evidence that nano-reinforcement is most efficient where the host matrix is more porous and the scope for pore refinement is greatest. Second, within each system, durability indices improve more than mechanical indices,

with chloride and water-permeability resistance showing the greatest gains. This confirms that GO functions foremost as a transport-network modifier, and only secondarily as a strengthening agent. Table 7 situates the present results within the recent literature, showing close agreement with reported optimum-dosage effects and confirming that the observed improvements are consistent with, and quantitatively bounded by, independently reported ranges.

Table 7: Comparison of present findings with recent literature on GO-modified concrete.

Study / source	System	Reported effect at optimum GO	Optimum
Present study	CC (M40)	+23.5% compressive; -40% RCPT	0.03%
Present study	HSSCC (M60)	+19.5% compressive; -46% RCPT	0.03%
Systematic review [7]	Pastes/mortars	+15-25% strength (typical)	0.03%
Strength study [6]	GO-cement	+46% compressive at 28 d	0.03%
SCC study [8]	SCC (M25-M40)	Strength ↑; absorption ↓	≈0.03%
Techno-economic [20]	Concrete	-50% chloride/permeability	0.02-0.10%
Durability review [2]	Concrete	Reduced permeability & absorption	≈0.03%

Conclusion

Based on the comparative experimental investigation of GO-modified conventional concrete and high-strength self-compacting concrete, the following conclusions are drawn:

- A distinct optimum dosage of 0.03% GO by weight of binder maximises performance in both systems; beyond this threshold, nanosheet agglomeration reverses the

gains, and the mechanical optimum coincides with the rheological ceiling of the self-compacting mixes.

- At the optimum, 28-day compressive strength rose by 23.5% (CC) and 19.5% (HSSCC), with split-tensile and flexural gains of ~24-26%, confirming that GO benefits fracture-controlled properties most strongly through crack bridging.

- Durability improvements exceeded strength improvements in every case: chloride penetrability and water-permeability depth fell by up to 45% and 55%, and acid mass loss by up to 45%, establishing durability enhancement as the principal engineering value of GO.
- Conventional concrete showed the larger relative improvement while HSSCC retained the higher absolute performance, demonstrating that GO efficiency scales inversely with baseline matrix density.
- Microstructural mechanisms—GO-templated C-S-H nucleation, pore refinement and micro-crack bridging—coherently explain the macro-scale behaviour and its reversal beyond the optimum dosage.

Future Scope

Several avenues merit further investigation. Long-term durability under coupled deterioration (simultaneous chloride-sulphate attack, carbonation and freeze-thaw cycling) should be evaluated to translate short-term indices into service-life predictions. The scalability and cost of achieving reliable GO dispersion at field-batching scale remains a practical barrier warranting dedicated study, alongside life-cycle and techno-economic assessment of the cement- and CO₂-reduction potential enabled by GO. Hybrid nano-systems—GO combined with nano-silica, hydroxylated graphene or fibres—offer scope for synergistic optimisation, while machine-learning-assisted mix design could accelerate dosage optimisation across grades. Finally, structural-scale validation on reinforced members, including bond behaviour and long-term rebar-corrosion monitoring, is needed before code-level adoption of GO nano-reinforcement in practice.

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